

**INTERNATIONAL ENERGY AGENCY
HYDROGEN IMPLEMENTING AGREEMENT
TASK 11: INTEGRATED SYSTEMS**

**Final report of Subtask A:
Case Studies of
Integrated Hydrogen Energy Systems**

Chapter 2 of 11

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Chapter 2

SOLAR HYDROGEN PLANT ON THE MARKUS FRIEDLI RESIDENTIAL HOUSE

1. PROJECT GOALS

Integrated solar hydrogen production plants are rare and are generally being built and tested by public institutions (universities, national energy agencies) or by utilities with a major involvement of public funds. In contrast, the present report describes a private installation in Switzerland which was built by its owner (Markus Friedli, CH-3436 Zollbrück) for domestic use, mainly from commercial components and so far, without funding from the federal government. The aim of this project was to prove that it is technically possible to implement and operate such a facility on the every day level.

Involvement of academia therefore only started after completion of the installation, with the objective to analyze the overall performance of the system as well as of the individual subsystems and to suggest possible improvements. This task was undertaken by an expert group of energy system analysis of the Centre d'étude des problèmes de l'énergie together with researchers in the field of metal hydride storage of the Laboratoire de cristallographie (Université de Genève, Switzerland), without external funding.

2. GENERAL DESCRIPTION OF PROJECT

2.1 Overview

The system is integrated into a one-family house and consists mainly of commercial components. It is operational since 1991 and is located in a region of moderate climate (altitude 630 m, latitude 46.9°N, average sunshine 1,540 h/year, corresponding to 4,020 MJ/m²/year). The system configuration (Figure 2.1) allows for the production and storage of hydrogen for both stationary (stove, laundry machine) and mobile applications (hydrogen or gasoline powered car); for PV electricity storage in a stock of lead acid batteries connected to the domestic grid; or for PV electricity feedback into public grid. Due to the manual control of the production mode, hydrogen production has actually been limited so far to demonstration purposes, so that the latter two storage modes still have priority.

Specific measurements combined with in-situ measurements, during operation on 3 typical summer days, allowed the characterization of individual subsystems and the determination of a disaggregated input/output diagram (instantaneous hydrogen production vs. solar radiation). Computer modeling based on later specifications and standard meteorological data enabled the determination of the yearly PV storage potential, under the hypothesis of hydrogen production having priority over the other storage modes.

2.2 System description

Solar radiation is transformed by PV panels into electric current which passes a control unit and a DC-DC converter before being transformed by an electrolyzer into chemical energy (hydrogen) or stored in batteries and/or injected into the grid. A small part of auxiliary energy is supplied by the electric grid for operation of the control unit, electrolyzer regulation, purification unit and hydrogen compressor. However, the electrolyzer can, in principle, also be operated from the public grid via an AC-DC converter. Water is needed as a feed, for cooling the electrolyzer, and for removing electrolyte from the hydrogen gas. Some hydrogen is consumed in the purification step, where any oxygen in the hydrogen stream is catalytically reacted with hydrogen. Hydrogen is transferred into an intermediate storage tank and then compressed for seasonal storage into a metal hydride storage tank. The latter is connected to house appliances such as a stove and a laundry machine (no longer in operation), and a second metal hydride storage tank is located in a minibus (which can alternatively also be fueled with gasoline). The household is exclusively powered by the battery stack via a DC-AC converter and is completely separated from the public grid.

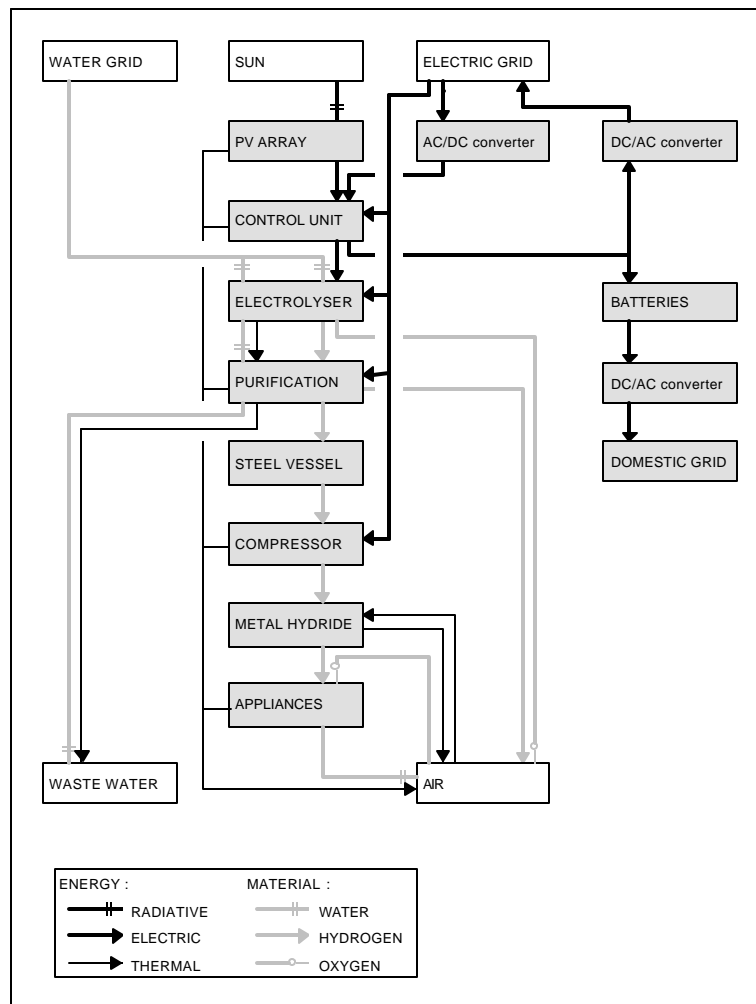


Figure 2.1: Schematic diagram of the system and energy/material flows.

3. DESCRIPTION OF COMPONENTS

3.1 Photovoltaic Field

The PV array consists of 162 solar panels, which are connected in series of 6 panels grouped into two subarrays (Picture 2.1). They cover a total surface of 65.2 m² (56.6 m² cell surface) and have a total nominal peak power of 7.4 kW_p (3.4 and 4 kW_p; for technical details see Table 2.1). The measured peak power during two sunny summer days (Figure 2.2) is much lower (4.5 kW_p), the discrepancy being mainly due to : 1) an overestimation of the panel performance by the supplier. The peak power as derived from U/I measurements and normalized for standard conditions, i.e. 1000 W/m² insolation and 25°C panel temperature, was found to be ~11% lower than the manufacturer rating; and 2) a loss of conversion efficiency due to the heating of the solar panels (up to 75°C at 1000 W/m² insolation).



Picture 2.1: PV-panels on house roof and minivan.

A quadratic regression on monitoring data for two summer days yields a PV base efficiency of 8.9% which decreases at a rate of 0.2% per 100 W/m² insolation. A more global estimation of the seasonal efficiencies was made by using the PV simulation computer program PVSYST (developed by A. Mermoud at the University of Geneva) and standard meteorological data available for that area. The values obtained vary between 9.7% (- 0.28% per 100 W/m²) for the summer season and 10.4% (- 0.23% per 100W/m²) for the winter season (see Table 2.1). The estimated yearly average panel efficiency is 8.4%.

3.2 Control unit and DC-DC converter

The unit consists of a regulator and a DC-DC converter developed and supplied by the Engineering School of Biel, Switzerland (Picture 2.2). Their main purpose is to maximize the

hydrogen production by matching the characteristics of the PV array and the electrolyzer (power point tracking), and to increase the charging efficiency of the lead acid batteries. Technical details are summarized in Table 2.2.

Table 2.1: Data for PV panels and array

Panels	Supplier	Siemens
	Model	Arcosolar M73 and M75
	Number of cells	33/panel
	Surface/panel	4.023 m ² (total), 3.494 m ² (net)
	Nominal power	M73 : 41 W, M75 : 48 W
	Real power*	M73 : 37.8 W, M75 : 41.6 W
	Temperature	max. 75°C
Array	Connection	in series of 6, grouped in two modules
	module 1	42 M73, 48 M75
	module 2	72 M75
	total surface	65.2 m ²
	orientation	10°SSE azimuthal, inclination 35°
	power	7.4 kW (nominal*), 6.6 kW (real**), 4.5 - 5.0 kW (measured)
	efficiency	summer : 9.7% - 0.28% per 100W/m ² insolation*** winter : 10.4% - 0.23% per 100W/m ² insolation*** midseason : 10.1% - 0.28% per 100W/m ² insolation*** yearly average : 8.4%

* for standard conditions (STC) of 1000W/m² insolation and panel temperature of 25°C.

** as derived from U/I measurements, normalized for STC by using the program PVSYST.

*** regression on hourly values as generated by program PVSYST with standard meteorological data.

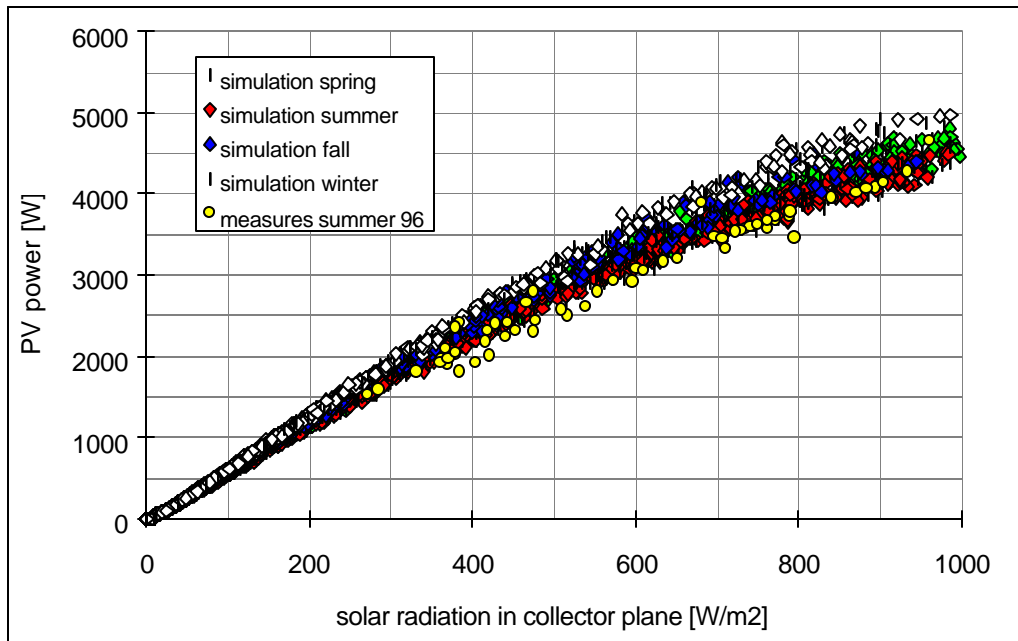


Figure 2.2: PV power versus solar radiation, measured over 2 summer days (5 min. step) and simulated over one year (hourly step).



Picture 2.2: DC-DC converter and integrated control unit

Table 2.2: Data for control unit and DC-DC converter

Supplier	Ecole d'ingénieurs de Bienne, CH-2501 Bienne	
Model	HMAX	
Voltage (V)	entry	70 - 150 DC
	exit electrolyzer	28 - 38 DC
	exit batteries	22 - 28.5 DC
Current (A)	entry	0 - 120 DC
	exit electrolyzer	30 - 300 DC
	exit batteries	0 - 300 DC
power (nominal)	11 kW (electrolyzer), 8.5 kW (batteries)	
auxiliary power	<30 W (950 MJ/year)	
dimensions	158x55x60 cm ³	
efficiency	96% at 1.8 kW entry and greater	

The system needs less than 30 W auxiliary power. Its average efficiency exceeds 95% (Figure 2.3) at an incoming power greater than 1.8 kW. Various modes of operation, which are manually selected, are possible, such as hydrogen production from the two PV modules connected in parallel; charging the batteries from the PV modules and optional hydrogen production from the grid; charging the batteries from the 4 kW module and injection of electricity from the 3.4 kW module into the grid with optional hydrogen production from the grid; and hydrogen production from the 4 kW module with injection of electricity from the 3.4 kW module into the grid. The installation of the DC-DC converter and the suppression of the initially installed DC-AC ondulator coupled to the AC-DC converter in the electrolyzer decreased the losses by about 20%.

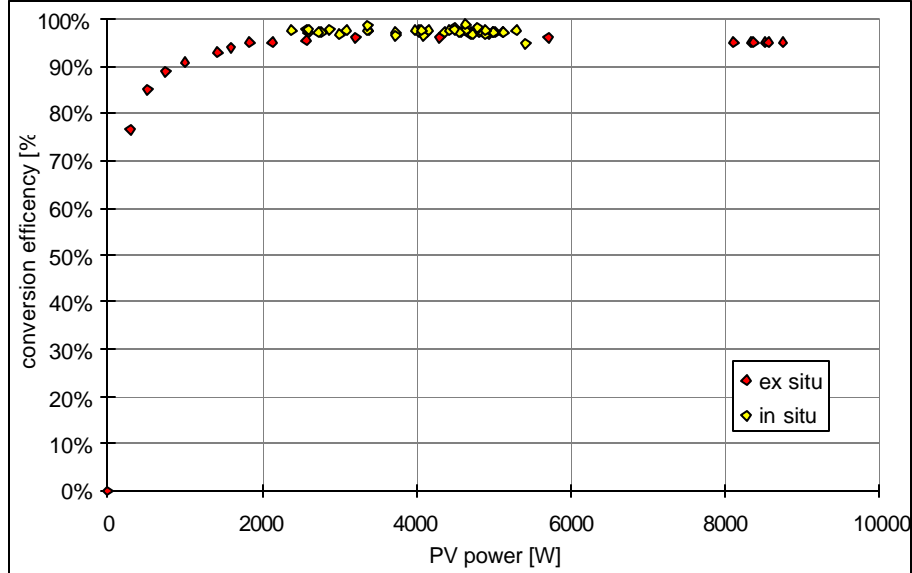


Figure 2.3: Measure of conversion efficiency at construction of unit (ex-situ) and during operation on a summer day (in-situ).

3.3 Electrolyzer

The commercial alkaline (KOH) type membrane model (Picture 2.3) was originally designed for continuous hydrogen production from the AC grid (for technical details see Table 2.3). It had a maximum power of 10 kW and yielded about 2 Nm³ hydrogen gas per hour at a pressure of 2 bar and a purity of 99.8%. For the present intermittent operation from PV power, the original AC-DC rectifier in the electrolyzer was replaced by a DC-DC converter and the operating power was limited to a lower threshold of 1.4 kW (1.8 kW at start-up) for reasons of safety, and to an upper threshold of 4.6 kW to minimize wear. These correspond to current limitations between 45 A (55 A at startup) and 130 A, and a hydrogen production between 0.32 Nm³ per hour (0.40 Nm³ per hour at startup) and 0.95 Nm³ per hour.

This unit also hosts an electronic regulation and display system which controls the electrolyzer as well as tracking the subsystems, basing on data like load, system pressure, purification temperature and storage capacity of metal hydrides. This regulation can be linked to a computer for on-line visualization of system operation and data acquisition.

Current versus tension characteristics at different operating temperatures (normal operating temperature being 45°C) were established by ex-situ measurements while bypassing the control unit and were compared to in-situ measurement in 5 minute steps on 3 typical operation days (Figure 2.4). Systematically higher voltage values at low current densities correspond to the start-up periods at the beginning of the day when the set-point temperature was not yet reached (see also Figure 2.6). The data shows the exponential rise of the cathodic and anodic overvoltages below 90 A, followed by a linear rise of the ohmic overvoltage. Correspondingly, electrolyzer voltage efficiency (defined by the ratio of the lower heating value of hydrogen and

the electric power used) decreases with increasing load, passing from 66% (65% at startup) at lower threshold to 60% at upper threshold. Resulting yearly average electrolyzer efficiency is 62%.



Picture 2.3: Electrolyzer and regulation display

Table 2.3: Data for electrolyzer

General data	supplier / model	VCST Hydrogen Systems (Belgium)/IMET 2	
	cell number	16	
	cell surface	600 cm ²	
	temperature	45°C (average), 50°C (setpoint)	
	pressure	2 bar	
	electrolyte	KOH (30 wt%, density 1.27 g/cm ³)	
	dimensions	0.60 x 0.80 x 1.79 m ³	
	maximum power	9.5 kW (37 V, 250 A), 2Nm ³ /h hydrogen	
Requirements	water	electrolysis	3 liter/Nm ³
		cooling of H ₂ gas	7.5 l/hour
		cooling of cells	40 liter/Nm ³
	regulation power	22 W (690 MJ/year)	
limitations for PV operation	power	1400 W (1800 W at start-up) - 4600 W	
	current	45 (55) - 130 A	
	hydrogen yield	0.32 (0.40) - 0.95 Nm ³ /hour	
	efficiency*	66 (65) - 60%, average 62% (LHV)	

* for standard conditions of 1000 W/m² insolation and panel temperature of 25°C.

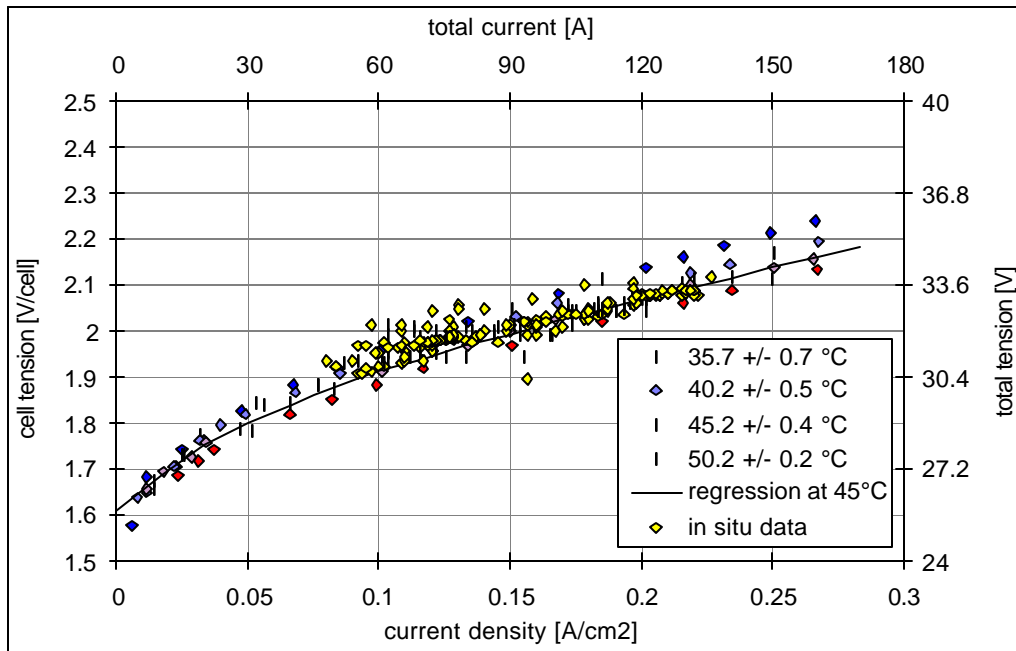


Figure 2.4: Electrolyzer current versus tension at different temperatures (triangles and squares), regression on the average operating temperature (solid line), and in-situ data in 5-min. steps over 3 operating days (crosses).

Some 22 W of electricity (from the grid) are needed for regulation, and up to 3 liters of demineralized water per hour for electrolysis. At full operation the total water consumption is about 40 liter/h, which includes about 30 liter/h for cooling.

3.4 Purification, intermediate storage and compression

The purification unit (Picture 2.4) is needed so as to enhance hydrogen purity to a level proper for storage in metal hydrides. It consists of a water bath, a condenser and a drying unit running on the grid. The bath removes traces of the KOH electrolyte and uses water from the cooling circuit of the electrolyzer. The condenser is filled with a noble metal catalyst that removes traces of oxygen. The drying unit consists of two molecular filters that remove water and are used in alternation. Originally designed to run under a constant hydrogen flow of 2 Nm³/h, they are now controlled by the electrolyzer regulation. They are capable of treating about 2 Nm³ wet hydrogen gas each and have to be regenerated by heating under a hydrogen flux. This requires rather high amounts of both electric energy (200 W during 45 min for heating to 85°C, and 60 W in equilibrium, corresponding to about 0.13 kWh/Nm³ hydrogen gas) and hydrogen gas (0.2 Nm³/hour). This represents an average loss of up to 8% of the total hydrogen generated by PV power.



Picture 2.4: Purification unit (on wall) and metal hydride storage tank (on ground).

The purified hydrogen gas is stored in an intermediate, cylindrically shaped steel vessel (Picture 2.5) of about 450 liter capacity in the pressure range between 1.9 bar (upper setting to start the compressor charging the metal hydride tank) and 0.6 bar (lower setting to stop the compressor). The corresponding useful capacity of the vessel per compressor cycle is about 0.59 Nm^3 hydrogen gas. In order to meet the operating conditions of the metal-hydride storage tank the gas is then compressed to about 29 bar by the compressor (for technical details see Table 2.4). This requires a few minutes time and some 0.125 kWh grid power per compressor cycle (0.763 MJ/Nm^3 , corresponding to 7.6% of the lower heating value of hydrogen). The estimated yearly average energy consumption is 810 MJ.

3.5 Metal hydride storage tank

The metal hydride storage unit is situated at the floor of the electrolyzer control room (Picture 2.5) and consists of a stack of metal cylinders which are filled with a hydrogen absorbing alloy (multi-substituted derivative of TiMn_2). They are embedded in a cooling circuit operating on tap water which speeds up thermalization during absorption (exothermic reaction) and desorption (endothermic reaction). The circuit was switched on only for testing of the performance of the storage tank, but is not used during normal operation of the system. The total tank volume and weight is 91 liters and 235 kg, respectively, including 15 liters and 100 kg, respectively, of the alloy (for technical data see Table 2.5).



Picture 2.5: Compressor and intermediate storage vessel (partial view on side of picture).

Table 2.4: Data for purification, intermediate storage and compression

Hydrogen purification unit	Dimensions	70 x 20 x 105 cm ³
	Temperature setting	85°C
	start-up heating time	45 min (from 25 to 85°C)
	heating power	60 W (200 W during start-up)
	estimated yearly average	510 MJ (0.13 kWh/Nm ³)
	hydrogen requirement	0.2 m ³ /hour
	pressure	2 bar
Storage vessel	supplier	Brand Anlagebau (CH)
	volume	454(+/-13) liter
	pressure	1.9 - 0.6 bar
	height	195 cm (total), 180 cm (vessel)
	diameter	60 cm
	H ₂ -capacity	0.59 Nm ³ (between 0.6 and 1.9 bar)
Compressor	Supplier	Corken (USA)
	Model	D191 AM4FBAB
	Power	3.2 kW, estimated yearly average 810 MJ
	Pressure	29 bar
	time/cycle	150 s
	power/cycle	0.125 kWh/0.59 Nm ³ (0.763 MJ/Nm ³)

Table 2.5: Data for metal hydride storage tank (in-house)

Supplier	Japan Metals & Chemicals
Pressure range	1.2 - 29 bar
Capacity	19 Nm ³ (nominal at 20°C, 30 bar)
Volume	15.2 Nm ³ (measured at 5.3°C, between 1.2 and 27 bar) 91 l (total), 15 l (metal hydride)
Weight	235 kg
Alloy composition	Ti _{0.98} Zr _{0.02} V _{0.43} Fe _{0.09} Cr _{0.05} Mn _{1.5}
Storage efficiency	1.8 wt% (alloy, total), 1.3 wt% (alloy, reversible) 0.54 wt% (tank, reversible)
Heat of absorption/desorption	14.4 MJ for 14 Nm ³

The storage characteristics of the metal hydride tank during absorption and desorption were measured during the winter season by using the thermalizing circuit of circulating tap water at 5.3°C (Figure 2.5). The total reversible hydrogen capacity as measured between 1.2 and 27 bar was 15.2 Nm³ (14 Nm³ in alloy, 1.2 Nm³ of compressed hydrogen in free volume). This quantity is similar to that of other metal hydride based PV hydrogen storage systems, but falls short by about 20% from the total capacity of 19 Nm³ as stated by the supplier. Likely reasons for this discrepancy are the difference between total and reversible storage capacity, aging, and the partial passivation of the metal hydride alloy due to contamination by impurities in the hydrogen gas during the past four years of operation. As expected, the failure to use the thermalizing circuit during normal operation reduced the actual storage capacity of the metal hydride tank further.

The tank is connected to a hydrogen-powered stove for cooking and a laundry machine (no longer in operation), and can be used to charge a mobile metal hydride storage tank in a minibus (Picture 2.6) having similar nominal characteristics (16 Nm³ capacity at room temperature and 40 bar pressure, 3 bar desorption pressure at -20°C). This application has not been analyzed to date.

4. INTEGRATION OF COMPONENTS

According to the owner and the engineer who set up the interconnection of the distinct units and the regulation, significant effort was expended for component integration and regulation adapted to dynamic solar production including:

- Construction of a specific DC-DC maximum power point tracker for coupling of PV field with electrolyzer or batteries and short cutting of initially integrated AC-DC converter in electrolyzer.
- Adaptation of purification unit to intermittent hydrogen production.
- Design of an electronic regulator for the electrolyzer and downstream units, compatible with variations in solar insolation.

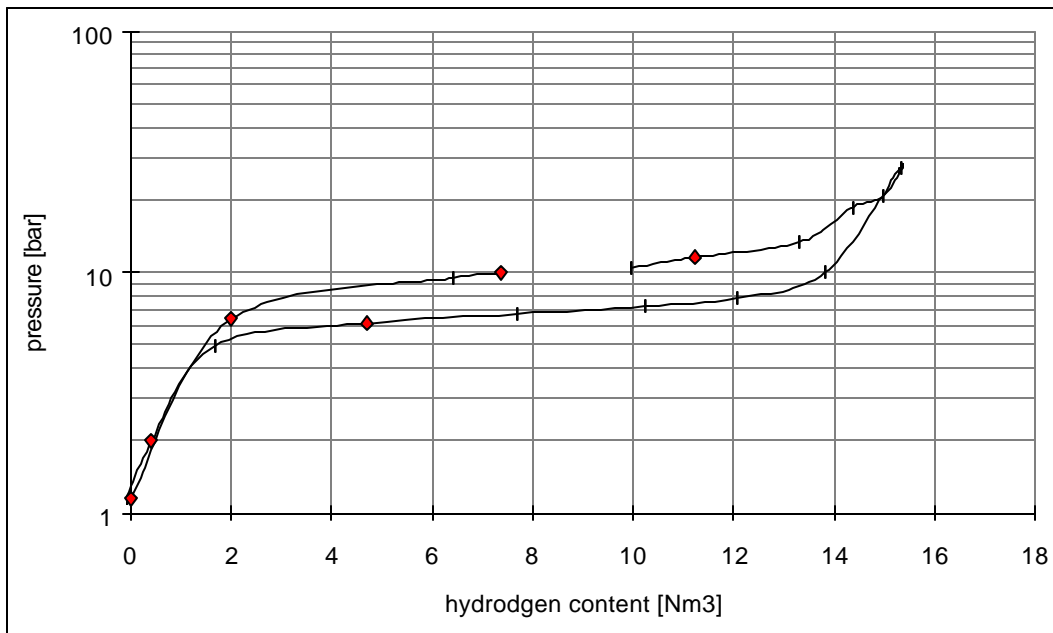


Figure 2.5: Pressure-composition isotherms of in-house metal hydride tank during absorption (upper curve) and desorption (lower curve) at 5.3 °C.



Picture 2.6: Metal hydride storage tank in minivan.

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

5.1 Daily performance

The performance of the system was evaluated by in-situ measurements during 3 summer days in 1996. Relevant data for one day (July 26) are presented in Figures 2.6 and 2.7.

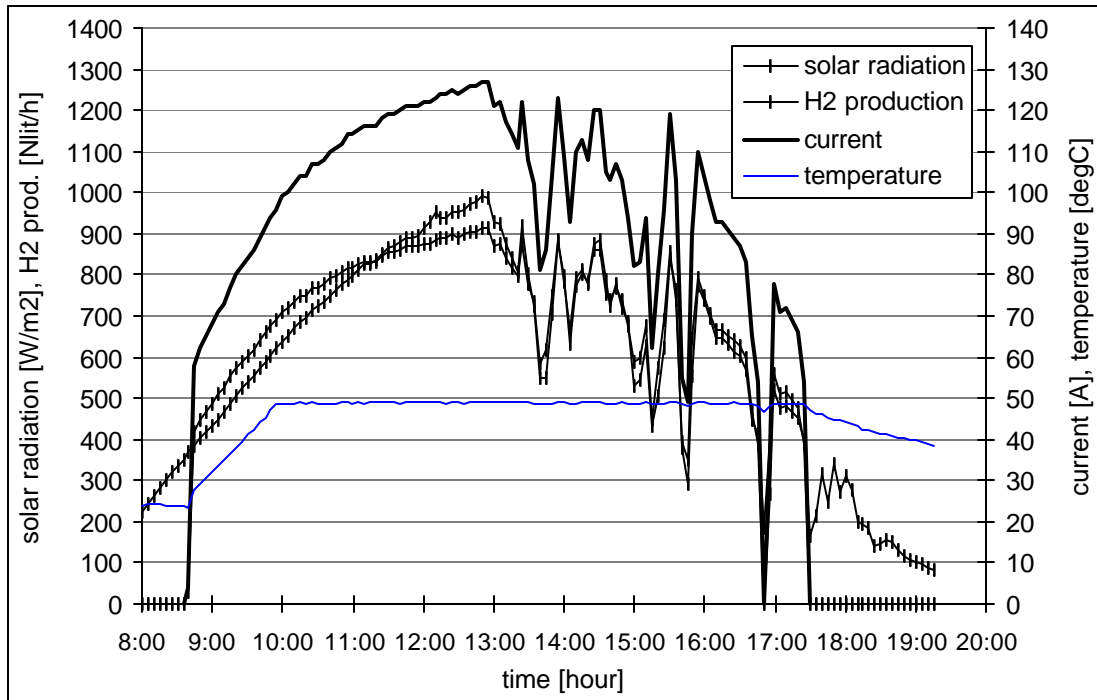


Figure 2.6: Hydrogen production on July 26th 1996.

Figure 2.6 shows the evolution of the insolation, hydrogen production, PV current and electrolyte temperature as a function of time. The weather conditions were sunny in the morning and cloudy in the afternoon. The measurements started at 08:00. The hydrogen production started at about 08:45 when the threshold setting of the electrolyzer (55 A, ~380 W/m² solar radiation) was met, and increased continuously as a function of time and insolation until noon. Note that the gross hydrogen production by the electrolyzer shown here was not actually measured, but calculated from the electrolyzer current, unlike the net hydrogen production after purification, which was measured by pressure differential in the intermediate storage tank. The electrolyzer temperature increased for about 1¼ hours until it stabilized at about 50°C at 10:00. The first clouds appeared around 13:00 and lead to strong variations in the electrolyzer current, including a complete switch-off of the electrolyzer shortly before 17:00, followed by an almost immediate switch-on, with the final switch-off around 17:30.

Relevant data for storage are presented in Figure 2.7. When the pressure in the intermediate storage tank reached 1.9 bar, the compressor switched on and the hydrogen was transferred into the metal hydride storage tank. At the upper pressure limit of the hydride tank, hydrogen was vented into the air.

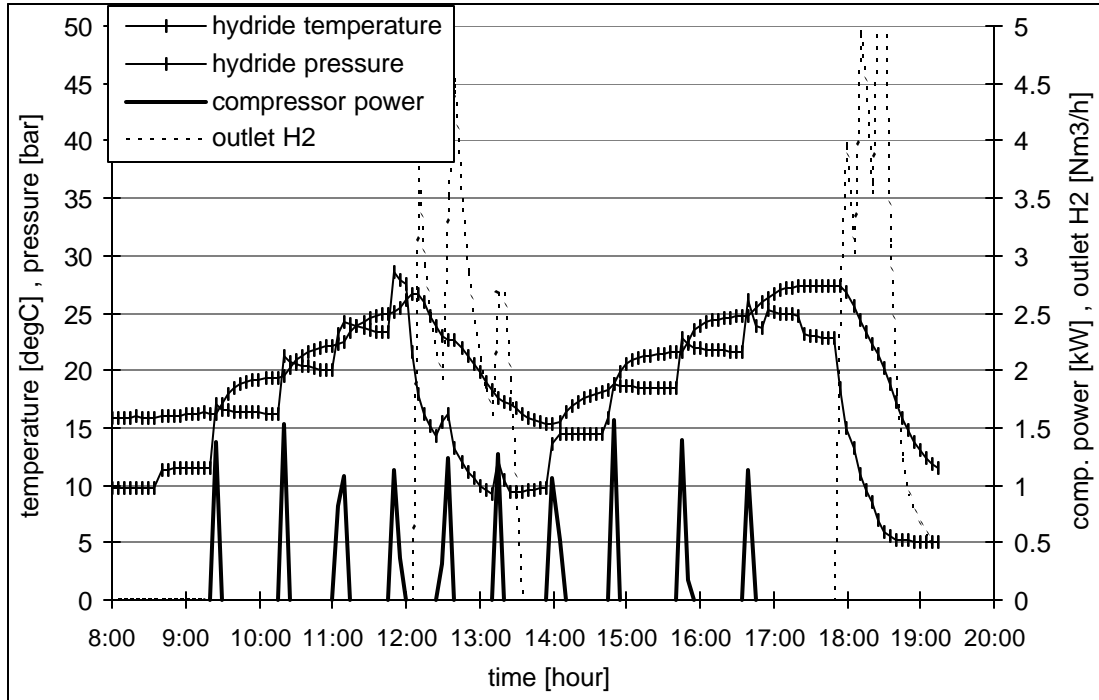


Figure 2.7: Hydrogen storage on July 26th 1996.

The graphs show the temperature and pressure in the hydride storage tank, the compressor power, and the rate of hydrogen venting as a function of time. During that day, the compressor switched on 10 times, corresponding to a total hydrogen production of about 6 Nm³. The temperature of the hydride bed increased from 15°C in the morning to 28°C at noon, while the pressure increased in intervals of about 1 hour stepwise from 10 to 30 bar, thus requiring a first venting of hydrogen at noon. A similar evolution was observed in the afternoon, requiring a second hydrogen venting in the evening. The total amount of vented hydrogen was 7.3 Nm³ (including H₂ production from the preceding day), which is largely below the measured total capacity of the metal hydride tank (15 Nm³). The failure to store the daily total production of hydrogen is due to the incomplete desorption of the metal hydride bed at the beginning of the measurements, and the inertia of heat transfer during absorption and desorption due to the failure to use the thermalizing circuit during operation. A summary of the system performance on that day and a comparison with the performance on two other summer days are shown in Table 2.6.

Table 2.6: Daily performance on 3 consecutive summer days.

Date	period of production	insolation		Photovoltaic		Hydrogen	
		total	during production	Gross ¹	net ²	Gross ³	net ⁴
	[hours]	[kWh/m ²]	[kWh/m ²]	[kWh]	[kWh]	[Nm ³]	[Nm ³]
26.07.96	8.8	6.6	6.1	(missing)	27.8	6.2	5.9
27.07.96	3.4	3.3	1.6	7.2	6.4	1.5	1.4
28.07.96	5.2	3.9	3	13.1	11.4	2.7	2.5

1) before DC-DC converter ; 2) after DC-DC converter ; 3) before purification ; 4) after purification

5.2 Disaggregation of instantaneous production

Measured efficiencies of the various system components allow for construction of a synthetic input/output diagram of hydrogen production as a function of solar radiation. Results are shown in Figure 2.8. For summer the resulting model is:

- Gross PV efficiency (before control unit) has a basis value of 9.7% with a decrease of 0.28% per 100 W/m² insolation, due to heating of cells.
- Net PV power is reduced by 4% due to energy losses in the control unit.
- Due to increase of ohmic losses with electrical power (see also electrolyzer U/I curve in Figure 2.4), gross hydrogen production efficiency falls from 66% at start-up threshold to 60% at maximum power. Yearly average is 62%.
- Net hydrogen production is reduced by 8% for regeneration of the hydrogen purification unit.

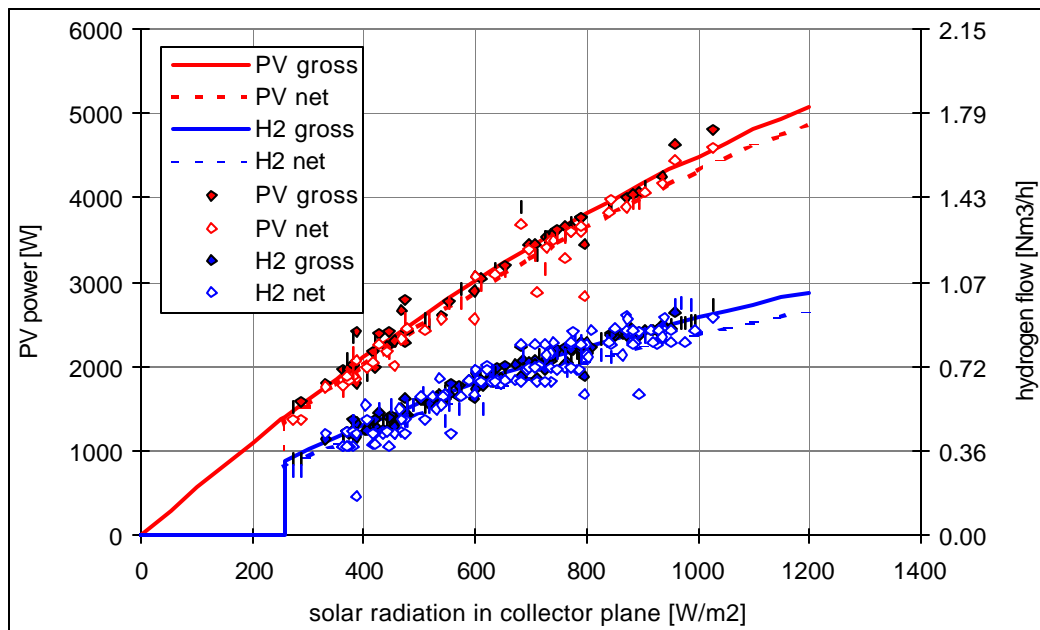


Figure 2.8: Summer input/output diagram (PV power and hydrogen production rate versus radiation in collector plane) and synthetic comparison between in-situ measurements in 5-minute steps (data points) and regressions (lines)

5.3 Simulation of yearly production and storage potential

Yearly hydrogen production potential was simulated using standard hourly meteorological data (temperature, incident solar energy) from a nearby meteorological station (Bern, 25 km away). Gross PV is derived using the computer program PVSYST as a more precise alternative to the mean seasonal efficiencies, while the other variables (PVnet, H₂gross, H₂net) are calculated in the same manner, as discussed earlier. The auxiliary power needed from the grid is evaluated by adding the steady power requirements of the control unit and the electrolyzer, the variable requirements of the purification unit during heating and at equilibrium, and the cyclic requirements of the compressor. Results are summarized in Table 2.7.

With a yearly total incident energy of 293 GJ and 65 m² PV panels (i.e. 4020 MJ/m²/year, corresponding to 1540 hours of sunshine with a direct incident radiation greater than 200W/m²), some 24.5 GJ of gross electric energy (23.4 GJ of net energy after the DC-DC transformer) are left for subsequent uses, corresponding to an average PV efficiency of 8.4%. Of the gross electrical energy available, only 18.6 GJ are powerful enough to drive the electrolyzer, while the rest (4.9 GJ) are stored in batteries and/or injected into the grid to compensate the auxiliary power (3 GJ) needed to operate the various components. From the 18.6 GJ used for water splitting, some 1148 Nm³ (11.5 GJ) hydrogen gas are obtained per year (average electrolyzer efficiency of 62%), of which 1056 Nm³ (10.6 GJ) remain after hydrogen purification and regeneration. This corresponds to an energy equivalence of about 300 liters of fuel and a hydrogen production potential of about 16 Nm³/m² of PV panels per year.

Table 2.7: Yearly hydrogen production potential

	Energy		Hydrogen	
	[GJ/yr]	[MJ/m ² /yr]	[Nm ³ /yr]	[Nm ³ /m ² /yr]
solar power:				
solar radiation	292.7	4491	29134	447.1
PV gross (after panels)	24.5	393	2546	39.1
PV net (after DC-DC converter)				
to electrolyzer	18.6	286	1854	28.4
to batteries/grid	4.9	75	489	7.5
Total	23.5	361	2343	35.9
Hydrogen gross (after electrolyzer)	11.5	177	1148	17.6
Hydrogen net (after purification)	10.6	163	1056	16.2
auxiliary power:				
DC-DC transformer	0.95	15	95	1.45
Electrolyzer	0.69	11	69	1.05
Dryer	0.51	8	51	0.78
Compressor	0.81	12	80	1.23
Total	3	45	294	4.5

The fraction of PV power stored in the form of chemical energy (hydrogen) thus amounts to 43%, while the net storage in the batteries and/or injection into the grid amounts to 8%, for an overall efficiency of 51% (electricity to storage energy). The total losses are 49%, comprised of 12% injected into the grid to compensate auxiliary energy use, 4% for DC-DC conversion, 29% for electrolysis, and 4% for purification. Thus the early average efficiency of the system for converting solar energy into chemical energy for seasonal storage is 3.6% (0.43×0.084), which is about 30 times bigger than that of photosynthesis.

As preceding analysis shows, performance of the present installation compares quite well with that of other PV hydrogen production plants.

Although operated only intermittently, hydrogen production has been running without major problems over some 7 years now. The sole major accident, at the beginning of the project, was due to carelessness during refilling of KOH into electrolyzer, which induced a short circuit that damaged the cell stack. Major shut down periods were only necessary for development and integration of the electronic regulation system of the hydrogen production and storage process.

The system nevertheless still lacks some minor, but nevertheless essential, optimization for long-term hydrogen production and storage:

- Installation of an automatic control unit, dependent on storage capacity: replacing the actual manual selection of the storage mode (hydrogen/batteries/injection into grid) would allow operation of the installation in absence of house inhabitants and thus increase efficiency.
- Increase of the hydrogen storage capacity: the estimated amount for seasonal hydrogen storage ($\sim 200 \text{ Nm}^3$ hydrogen gas, assuming a uniform consumption over the year) requires storage capacity that is ten times bigger.

Although not essential for long-term storage, replacement of the hydrogen purification unit by one that does not consume hydrogen would also significantly contribute to an increase in the net hydrogen production.

6. SAFETY

Safety measures were implemented at the following levels:

System layout:

Subsystems containing significant amounts of gaseous hydrogen are located in a light shelter separated from the production and final hydride storage room.

Production control:

Regulation cuts hydrogen production when certain parameters exceed minimum/maximum thresholds. These include pressure in the production system (electrolyzer, purification) and the intermediate and final storage units, water level in the electrolyzer H_2/O_2 columns, and purity of H_2 production.

Alarm:

When sensors near the production system and appliances detect hydrogen concentrations in air exceeding 0.1%, the alarm flashes and sounds an audible signal. Production is halted.

A manually operated alarm button allows evacuation of the hydrogen from the production and intermediate storage units.

7. ENVIRONMENTAL ASPECTS

An investigation of environmental implications of hydrogen-gasoline propulsion in the minivan was conducted in collaboration with the Swiss federal laboratories for materials testing and research (EMPA, Dübendorf) and will soon be presented in the frame of a diploma thesis at the Université de Genève.

8. FUTURE PLANS

From the point of view of practical application, integration of the plant into a one family house makes this facility particularly interesting. Interconnection with battery storage for household appliances furthermore optimizes rational use of photovoltaic electricity, which can also be used when PV power is below the electrolyzer threshold. With the experience gained, institutions involved in energy issues are now being approached for funding of the necessary optimization still to be done, as well as for monitoring and analysis of long term operation.

Parallel to this real scale work on a demonstration facility, a techno-economical analysis of the photovoltaic hydrogen production path on an industrial scale has been initiated by an interdisciplinary group of the Université de Genève.